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Applying CFD Technology to Determine the Effect of Two New Designed Fan Inlet Distortion Generators

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Abstract

Inlet distortion is a main resource of performance decreasing of compressor, in this way it is essential to judge the influence of inlet distortion to the compressor performance according to the test. A properly designed distortion generator can simulate the practical distortion condition exactly, which is a key and foundation to a successful distortion test. A new designed distortion generation requires proper methods for assessing the effect, while the naissance and development of computational fluid dynamics (CFD) provide an easy and effective way for this purpose. In this article two kinds of steam injectors were introduced for a fan steam injection test as distortion generator, and CFD technology was applied to simulate the effect of the schemes in order to obtain the flow field at test article inlet, and based on which the schemes were analyzed and examined. The better one was chosen from the two to make preparation for the final test. The test result will be used as a criterion to judge and modify the simulation project, then with the optimized distortion generator, a more proper test scheme will be erected.

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Keywords: distortion generator; distortion index; total temperature distortion; total pressure distortion; steam injector; numerical simulation

1. Introduction

Higher speed and altitude of a flight, larger mobility, as well as the application of weapons such as missiles, all of which lead to a serious temperature and pressure distortion at inlet of the engine. As a matter of fact, an adverse effect to the performance and stability of engine occurs [1]. For this reason, it is a must to take the influence of

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distortion to the engine into consideration when processing a design. By designing a successful distortion generator, one can simulate the practical inlet distortion condition as much as possible, and determine the effect of distortion to the engine's performance. Generally speaking, four or more years will be cost to process a test project before the first flight of an airplane, while the main job centers upon compressor [2], and designing a distortion generator shall be the first step to a successful distortion test, on which the researchers have done a lot of work, and make quite a lot of excellent results. But with the technology going on, numbers of new types of engines come along, which requires more types of distortion generators to satisfy the requirements of distortion tests.

Changing and developing the former types of distortion generators to produce a new type of distortion generator to satisfy the special requirements of a certain distortion test can reduce the time of design, cut the cost and make a decrease of mistakes. However, there must be some proper technology ways to examine and validate a new designed distortion generator, or else a false design may be produced, leading to an incompetent inlet distortion flow field and a failure of test, even threaten the safety of test article and apparatus. The naissance and development of computational fluid dynamics (CFD), as well as the accommodation and application of simulation technology offer an easy and efficient way to examine the distortion generator. According to the simulation result, one can not only understand the influence of distortion generator to the test article inlet preliminarily before a test, but also guide a modification and optimization base on the former scheme and obtain a better one. For this reason, there are very important meaning and application future.

In this article the action of distortion generator for a certain compressor distortion test was simulated in a CFD way, and the results was compared with the former test result to see whether the simulation was appropriate or not. Then, two new designed distortion generators were simulated in the same way, and a judgment was produced after analysis. Meanwhile, the proper distance between the relative distortion generator and test article inlet was determined as well.

2. Comparison between simulation and test results of a fan pressure distortion test inlet flow field

One pressure distortion test for a fan was accomplished, in which a distortion screen was used as the distortion generator. This type of distortion generators is proposed by Russia to be applied as spoilers in pressure distortion test, and is widely used for engine study and finalizing design [3].

Generally speaking, the distortion screen appears as chord-shape structure, which is settled inside a section of straight pipe at upstream of test article, just in front of the inlet of test article, and the ratio of area of screen to the total inlet area is called blockage ratio. The allocation of the distortion screen and the main parameters is shown in Fig. 1:

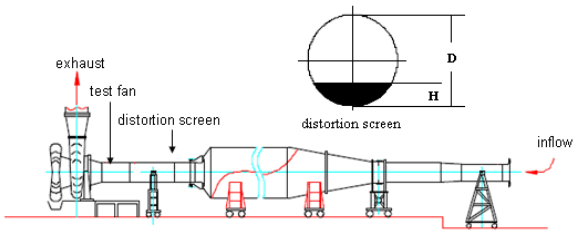

Fig. 1. Distortion screen allocation and the main parameters

Apparently, the height of the screen H and the diameter of inlet of the test article D determine the relative blockage ratio. In this fan pressure distortion test the blockage of screen was 15%, which means H≈0.21D.

Processing modeling for the distortion generator in front of inlet of fan, and the result is shown in Fig. 2:

Applying ANSYS ICME for meshing, the mesh type was hexahedral mesh, and the number was about 400 thousand.

ANSYS CFX was used to carry on the simulation, with the turbulence model KE model, and practical gas was used as working fluid. The inlet total pressure and flux of outlet was given according to the practical test in order to accept a simulation result of flow in the straight pipe. Furthermore, the total pressure distribution at inlet of test article was also acquired from the simulation result, which was used as a comparison to the one from test result, see Fig 3.

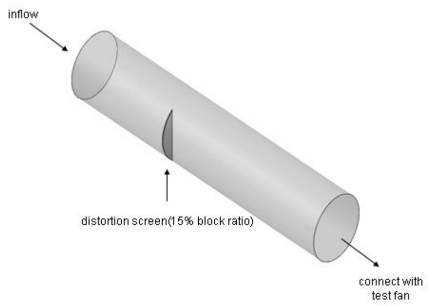

Fig 2. Modeling of the flow in the straight pipe at upstream of fan inlet

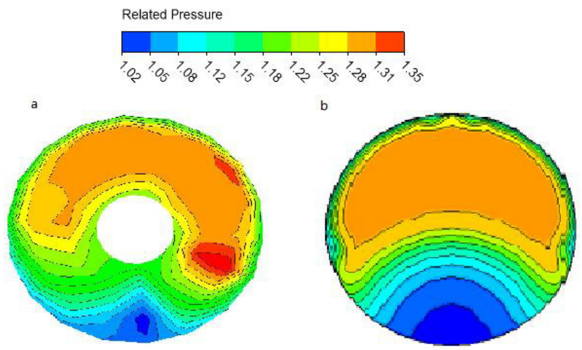

Fig. 3. (a) a total pressure distribution at inlet(test result); (b) a total pressure distribution at inlet(simulation result)

According to the comparison to (a) and (b) in Fig. 3 it can be seen that the total pressure distribution characteristics of simulation result were nearly the same to the test result, both of which perform distinct high pressure zones and low pressure zones, and the low pressure zones allocated at the bottom of the entire inlet, which responded to the location of distortion screen. With the pressure higher, different pressure zones appeared to be diffused from bottom to top. However, there were a few small differences between the two results. To put it in more accurate words, unlike simulation result, test result performed to be more distinct between high pressure zone and low pressure zone from the test result, and the total pressure distribution appeared not to be exactly symmetrical along vertical, when the low pressure zone transformed to high pressure zone, the non-symmetrical characteristic became more distinctly; meanwhile, the test result showed that there were two extremely high total pressure zones(the red ones in figure. 3)with small area at the section, while there were no such zones for the simulation result. One possible reason of these differences may be that during the test, because of the influence by the rotation of fan, the flow at downstream of test article inlet would affect total pressure distribution at fan inlet in some grade, which made total pressure non-symmetrical distribute at inlet, and strengthen total pressure distortion degree.

What should be pointed out is that the test article inlet was an annular one, while in the simulation, in order to get an integrated total pressure distribution and decrease the difficulty of simulation, the section was simplified to a circle one. Take comparison of simulation and test results for a further analysis we know that this simplification does not made too much influence to the accuracy.

Calculate the steady pressure distortion index $\Delta\sigma_0$ at test article inlet according to simulation result, which is defines as follow:

$$\Delta\sigma_0 = 1 - \sigma_0 / \sigma_{cp} \quad (1)$$

In which: σ_0 is the average value obtained by integral of total pressure alone radial and circumferential directions at the measured section; σ_{cp} is the average value of all the pressure survey points at the measured section [4].

According to the calculation, the inlet steady pressure distortion index $\Delta\sigma_0$ was 5.92%, which was equal to the one obtained from test result.

After analyze the comparison between simulation result and the test one it is believed that this simulation can reflect to the flow situation during the test, the result obtained by this method performs high reliability.

3. Requirements of new designed distortion generators and the designed forms

3.1. Brief introduction of design requirements and schemes

Now there is another kind of distortion test to be achieved on the fan described above, which require to design a new distortion generator, by which certain amount of high temperature steam is injected to the test article inlet, with the flux takes about 2% of total one, meanwhile the steam injected shall allocate 25% of total inlet area, while after mixing with inflow air the total temperature of steam shall fall no more than 100℃.

Based on the requirements above, there were two types of distortion generator being designed, which were shown in (a) and (b) in Fig 4 respectively, and were called scheme 1 and scheme 2 for short:

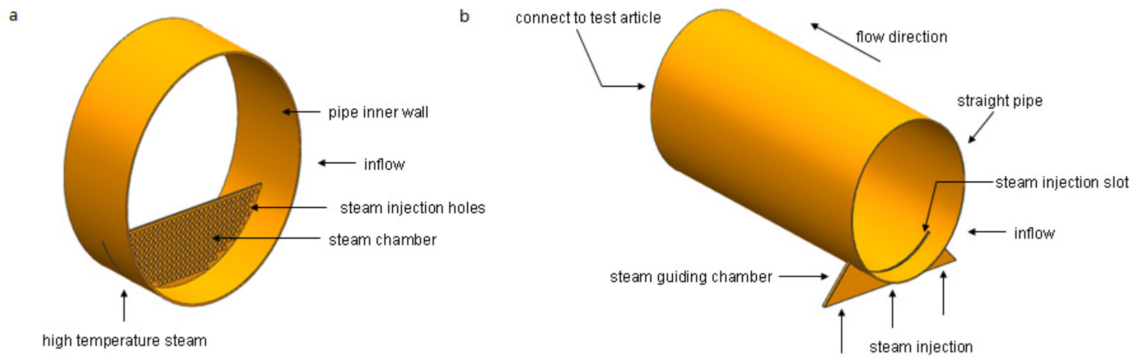

Fig.4. (a) scheme 1(outer wall not mark out); (b) scheme 2

After accomplishing the design of injector, location of test article inlet should be ascertained as well, which means make sure the axial displacement *l* between steam injection sections and test article inlet. In a distortion screen total pressure distortion test, the value of *l* shall satisfy the relationship: *l*=2.5~3.0D, for that there were materials showed that when the flow passed the screen, at the location of 2.5D the second swirl would occurred, so at this location the degree of total pressure distortion would arrive to the largest [5]. If the first stage of rotor right allocated at this location, the largest influence to the performance of test article would occur at the same time. However, for this situation, what is concentrated is inlet total temperature distortion introduced by the injected steam, and its influence to the performance of test article, so the influence of pressure distortion must be reduced to a minimum degree while strengthen total temperature distortion as much as possible. Because of that, for each certain distortion generator, it is essential to take both the influence of pressure distortion and temperature distortion into consideration along with guaranteeing the design requirements and choose special value of *l* for each scheme. That is to say, every optimum *l* for a distortion generator respectively.

In order to analyze the degree of distortion from simulation result in an easy way, define the following distortion index to consider the degree of distortion. For total pressure distortion index, the expression is:

$$\kappa = \frac{\overline{P^*_{low}} S_{low}}{\overline{P^*} S} \tag{2}$$

Similarly, the total temperature distortion index is:

$$\tau = 1 - \frac{\overline{T^*_{low}} S_{low}}{\overline{T^*} S} \tag{3}$$

In the expressions above, $\overline{P^*}$ and $\overline{T^*}$ refer to the average value of total pressure and total temperature at a certain section, and the zones with total pressure and total temperature lower than the average values are called low pressure zones and low pressure zones respectively, while the total pressure and total temperature at low value zones are presented as $\overline{P^*}_{low}$ and $\overline{T^*}_{low}$ respectively. Now the two schemes described above were introduced and the simulation results were analyzed respectively.

3.2. Brief introduction of scheme 1 and its simulation result analysis

See (a) of Fig. 4, scheme 1 is mainly constructed by a two-layer straight pipe located at upstream of test article and a chord-shape steam chamber. The high temperature steam generated by a boiler firstly passes through the inlet of straight pipe outer wall into the cavity between the outer wall and inner wall of straight pipe, then injects into the straight pipe from the holes in the wall of the chamber right at side near the test article inlet. This design refers to a retrofit of distortion screen, by which the installation possesses the function of injecting steam. Because of a small ratio of steam flux to the total one it affect little to the total pressure distribution at test article inlet, the main source of inlet pressure distortion comes from injector itself, namely the characteristic of total pressure distortion is the same to that of screen pressure distortion test. Carry on simulation modeling for scheme 1, simplify the form of steam injection sections for an easy meshing, consider the injection section to be a whole side wall of chord-shape chamber, the steam is injected along inflow direction, which is shown in Fig. 5:

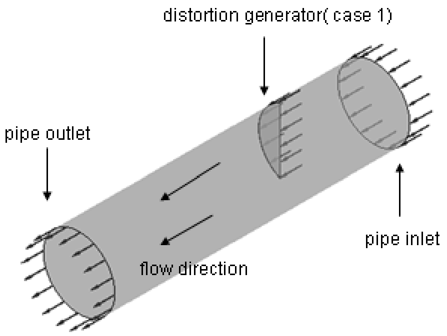

Fig. 5. Schematic of simulation modeling and boundary conditions

At the beginning of the simulation total pressure at inlet of straight pipe and flux of outlet was given, and the flux of high temperature steam was restricted to a certain amount. The total pressure at steam injection section was an examining parameter which need to be checked out for a prepare of pressure regulating in the practical test stage.

It is important to understand the distribution of total pressure and temperature at different aerodynamic interface planes (AIPs), so every 500mm there was a section along the axial direction settled to determine the distribution condition of total pressure and temperature. In this way an optimum l is chosen for the scheme. The sections were shown below in Fig. 6.

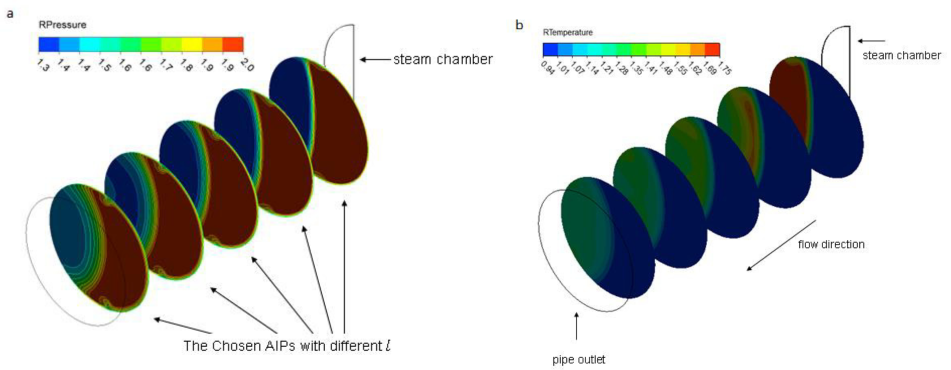

Fig. 6. (a) Total pressure distribution at different AIPs; (b) Total temperature distribution at different AIPs

From Fig. 6 it can be seen that after installation of steam injector of scheme 1, strong total temperature and pressure distortion appeared at each AIP along flow direction, the range of distortion more than 25% of total area of AIP. According to the expressions of total pressure and temperature index above, the relative indexes were calculated for each AIP, as was show in table 1:

Table 1. Total pressure and temperature distortion indexes at AIPs

	AIP01	AIP02	AIP03	AIP04	AIP05
Total pressure distortion index	0.463	0.494	0.517	0.534	0.551
Total temperature distortion index	0.466	0.496	0.514	0.527	0.544

From table 1 it can be seen that both the total pressure and temperature indexes at each section rose along the inflow direction, meaning a growth of total pressure and temperature distortion degree. Couple table 1 with Fig. 6, it is believed that the nearest section to the steam injector, namely AIP01 is the most suitable location as the test article inlet, because at which the total temperature distortion degree goes to the highest while the total pressure distortion degree goes to the lowest. Meanwhile, according to the simulation result, the total temperature of steam fell less than 100℃.

It should be pointed out that scheme 1 is a modification of distortion screen to add a steam injection function, but this doesn't change the essential of distortion screen as a pressure distortion generator, so for this scheme strong pressure distortion will occur at test article inlet combines with temperature distortion, which will of course be a risk to the performance of test article, and a difficulty for analyzing the influence of temperature distortion to the performance separately, so a hard changing of scheme 1must be processed to decrease the degree of pressure distortion.

3.3. Brief introduction of scheme 1 and its simulation result analysis

Since the application of scheme 1 will rise a serious inlet total pressure for sure, and no efficient way to reduce this right now, another distortion generator was designed as shown in (b) of Fig. 4, and was named scheme 2:

The structure of scheme 2 is very simple. In the inner wall of the straight pipe a slot was settled, the slot connected with a steam guiding chamber. In a test, the steam will first goes from a boiler to the steam guiding chamber through a steam pipe line, and then be injected into the straight pipe from the slot. By the force of inflow, the steam will goes to the test article inlet and form a distortion zone. The steam guiding chamber is a flabelliform cavity with a 90° central angle.

Process a simulation for this scheme, the boundary conditions are given as the ones of scheme 1, and the modeling is shown in Fig. 7:

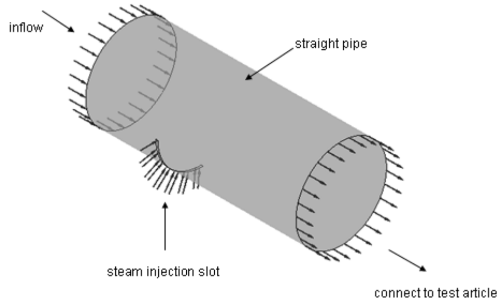

Fig 7. Modeling of scheme 2

Examining the distribution of total pressure and temperature at each section along flow direction, which are shown in Fig. 8.

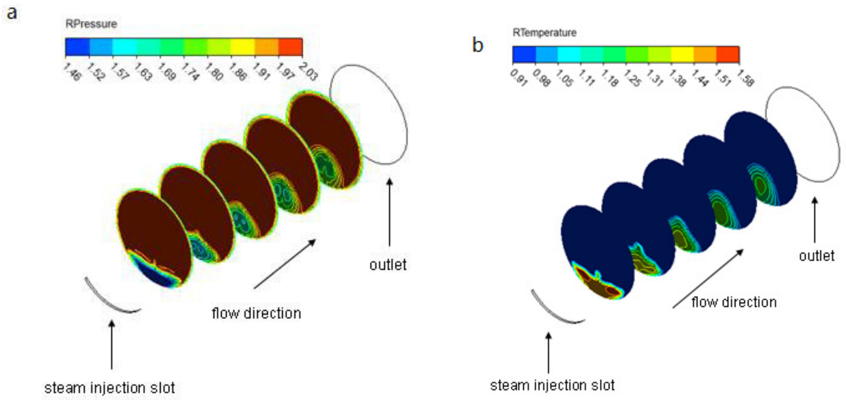

Fig. 8. (a) Total pressure distribution at different AIPs; (b) Total temperature distribution at different AIPs (scheme2)

Compare (a) and (b) in Fig. 8 one can see that the distortion zones of total pressure and temperature are nearly the same, while along the flow direction, the trend of changing of total pressure and temperature are the same as well. This means when applying this scheme, both the sources of total pressure and temperature distortion are from high temperature steam, while the pressure and temperature of steam can be adjusted during the practical test to achieve a required inlet distortion flow field.

Now the total pressure and temperature distortion indexes at each section were calculated as below, which can be seen in table 2:

Table 2. Total pressure and temperature distortion indexes at AIPs (scheme 2)

	AIP01	AIP02	AIP03	AIP04	AIP05
Total pressure distortion index	0.183	0.205	0.231	0.262	0.290
Total temperature distortion index	0.188	0.199	0.211	0.225	0.240

In table 2 one can see that the total pressure indexes at all sections of scheme2 are largely decreased, meaning that no such serious pressure distortion has been formed as scheme 1, however the total temperature indexes decreased as well, so it is essential to introduce another parameter to declare the effect of designs. In this article the ratio of total temperature distortion index to total pressure distortion index, namely τ / κ, is applied for this purpose, the calculation results is shown in table 3:

Table 3. Values of τ/κ at each section of the two schemes

	AIP01	AIP02	AIP03	AIP04	AIP05
scheme 1	1.006	1.004	0.994	0.989	0.987
scheme 2	1.027	0.970	0.913	0.859	0.828

In table 3 one can know clearly that the value of τ/κ at AIP01 of scheme 2 is the largest, namely in this condition the effect of total temperature distortion is the most distinct. Considering other factors such as test safety, performance decrease of test article and data solution after the test, scheme 2 shall be a better chosen for the test, and AIP01 of this scheme shall be chosen to be the test article inlet.

4. Conclusions

At the beginning of this article CFD technology was used to simulate a fan total pressure distortion test to study the influence of distortion screen to the test article inlet flow field, and the result was compared to the one from the simulation. The comparison showed that the two results were nearly the same, meaning that the simulation is available to reflect the flow field in a practical test. The calculated steady pressure distortion index of simulation was of little different to that of the test, the reliability of simulation is validated.

Then, to process a steam injection test, two different schemes of distortion generator were introduced in this article, and evaluation was carried on by CFD technology. The simulation result showed that considering the test requirements accompany with other factors such as test safety, reliability as well as data solution after test, scheme 2 with slot structure is better than scheme one with chord-shape steam injector, and the structure of which is simpler for installation, more suitable to be applied in the following test. Furthermore, the test article inlet shall be located at AIP01, the nearest section to the steam injection slot, which can also define the relative location of test article and distortion generator.

What must be pointed out is that during a simulation, set up of boundary conditions, simplification of the model, quality and density of mesh as well as turbulence model will affect the result of a simulation, especial for boundary conditions set up will do a lot to the accuracy and stability of simulation result. A new designed scheme is lack of test data support, the boundary conditions setup will of course different from practical conditions, so it is essential to process a modification to the simulation result according to the following test result to have an better simulation result, then optimize the design scheme and finally accomplish serving the test. This kind of circulation as simulation predicting- test verification- boundary condition modification- design scheme optimization- test application can decrease the time used for design and test, cut the cost as well, and finally obtain an optimum design and test scheme. The following job will be taken on base on this method to improve the design of distortion generator and finally apply to the steam injection test to study the influence to the test article performance.

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